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# An Investigation of Interval Management Displays

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February 2015

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## Abstract

NASA's first Air Traffic Management (ATM) Technology Demonstration (ATD-1) was created to transition the most mature ATM technologies from the laboratory to the National Airspace System. One selected technology is Interval Management (IM), which uses onboard aircraft automation to compute speeds that help the flight crew achieve and maintain precise spacing behind a preceding aircraft. Since ATD-1 focuses on a near-term environment, the ATD-1 flight demonstration prototype requires radio voice communication to issue an IM clearance. Retrofit IM displays will enable pilots to both enter information into the IM avionics and monitor IM operation. These displays could consist of an interface to enter data from an IM clearance and also an auxiliary display that presents critical information in the primary field-of-view. A human-in-the-loop experiment was conducted to examine usability and acceptability of retrofit IM displays, which flight crews found acceptable. Results also indicate the need for salient alerting when new speeds are generated and the desire to have a primary field of view display available that can display text and graphic trend indicators.

# Contents

<b>1</b>	<b>Introduction</b>	<b>6</b>
<b>2</b>	<b>Background</b>	<b>7</b>
<b>3</b>	<b>Experiment Design</b>	<b>8</b>
3.1	Experiment Procedure and Scenario Design . . . . .	8
3.1.1	Scenario Design . . . . .	8
3.1.2	Experiment Procedure . . . . .	9
3.1.3	Participants . . . . .	9
3.2	Pilot Tasks . . . . .	9
3.3	Data Entry Interface . . . . .	10
3.3.1	Menu-Entry . . . . .	12
3.3.2	Multi-Entry . . . . .	13
3.4	Primary Field-Of-View Displays . . . . .	14
3.4.1	Numerical AGD . . . . .	14
3.4.2	Graphical AGD . . . . .	15
3.5	Facilities . . . . .	16
3.5.1	Simulators . . . . .	16
3.6	Experiment Design and Independent Variables . . . . .	17
3.7	Experiment Limitation . . . . .	19
<b>4</b>	<b>Results: Data Entry Phase of Flight</b>	<b>19</b>
4.1	Pilot Workload . . . . .	19
4.2	Acceptability of Data Entry Time . . . . .	19
4.3	Intuitiveness . . . . .	20
4.4	Frustration Associated with the EFB Interfaces . . . . .	21
4.5	General Pilot Comments . . . . .	21
<b>5</b>	<b>Results: Monitoring Phase of Flight</b>	<b>22</b>
5.1	Pilot Acceptability and Workload . . . . .	22
5.1.1	Pilot Workload and Situational Awareness . . . . .	22
5.1.2	Intuitiveness of Displays . . . . .	23
5.1.3	Understanding of IM commanded speeds . . . . .	24
5.1.4	Usefulness of Symbology on Displays . . . . .	24
5.2	Pilot Performance . . . . .	26
5.3	Spacing Algorithm Performance . . . . .	27
<b>6</b>	<b>Conclusions</b>	<b>28</b>
	<b>References</b>	<b>29</b>
	<b>Appendix A: Post-Scenario Survey</b>	<b>31</b>
	<b>Appendix B: Post-Experiment Survey</b>	<b>37</b>

## List of Figures

1	Menu-entry EFB display CDTI page . . . . .	12
2	Menu-entry EFB display data input menu . . . . .	12
3	Menu-entry EFB display CDTI page . . . . .	13
4	Menu-entry EFB display data input menu . . . . .	13
5	Multi-entry EFB display CDTI page . . . . .	14
6	Multi-entry EFB display data input page . . . . .	14
7	Numerical AGD . . . . .	14
8	Graphical AGD . . . . .	15
9	Dual crew desktop simulator displays . . . . .	17
10	Pilot ratings describing whether they agreed that the amount of data entry was acceptable . . . . .	20
11	Pilot ratings describing whether they agreed that the EFB interface was intuitive . . . . .	20
12	Pilot ratings describing whether they agreed that the EFB interface was acceptable . . . . .	20
13	Pilot ratings describing whether they agreed that the IM displays provided adequate situational awareness . . . . .	23
14	Pilot ratings describing whether they agreed that the IM displays were intuitive . . . . .	23
15	Pilot ratings describing whether they agreed that the IM commanded speeds made sense to them . . . . .	23
16	Usefulness ratings of primary field-of-view display symbology . . . . .	25
17	Pilot reaction time to new IM commanded speeds . . . . .	26
18	Histograms of IM speed change rate . . . . .	28

## List of Tables

2	Data Pilots were required to enter . . . . .	11
3	Experiment design during data entry phase of flight . . . . .	18
4	Experiment design when monitoring IM . . . . .	18
5	Delivery accuracy and precision at the final approach fix . . . . .	27



## List of Acronyms

<i>ADS-B</i>	Automatic Dependent Surveillance-Broadcast
<i>AGD</i>	ADS-B Guidance Display
<i>ANOVA</i>	Analysis of Variance
<i>ASTAR-11</i>	Airborne Spacing for Terminal Arrival Routes (version 11)
<i>ATD-1</i>	1 <sup>st</sup> ATM Technology Demonstration
<i>ATM</i>	Air Traffic Management
<i>CAS</i>	Calibrated Airspeed
<i>CDTI</i>	Cockpit Display of Traffic Information
<i>EFB</i>	Electronic Flight Bag
<i>FAA</i>	Federal Aviation Administration
<i>ID</i>	(Aircraft) Identification
<i>IM</i>	Interval Management
<i>LaRC</i>	Langley Research Center
<i>LED</i>	Light-Emitting Diode
<i>MCH</i>	Modified Cooper Harper
<i>MCP</i>	Mode Control Panel
<i>NASA</i>	National Aeronautics and Space Administration
<i>OPD</i>	Optimized Profile Descent
<i>TRACON</i>	Terminal Radar Approach Control Facility

# 1 Introduction

Over the next twenty years, the Federal Aviation Administration (FAA) is predicting a substantial increase in the number of revenue passenger miles flown [1]. To accommodate the increase in traffic, the efficiency of the national airspace system must be increased. Interval Management (IM) is one concept that has demonstrated the ability to help aircraft achieve precise spacing intervals at the runway and enable the use of Optimized Profile Descents (OPDs) in high density airspace [2].

IM uses on-board avionics to enable aircraft to either achieve or maintain precise spacing behind a target aircraft. The IM automation includes an airborne spacing algorithm that uses Automatic Dependent Surveillance-Broadcast (ADS-B) data from the target aircraft to compute IM commanded speeds that the pilots follow to precisely achieve the spacing interval. The National Aeronautics and Space Administration's (NASA) Langley Research Center (LaRC) has been developing an implementation of IM that uses a trajectory-based spacing algorithm to compute commanded speeds, enabling an aircraft to perform IM operations when their target aircraft is on a different route. The trajectory-based IM application is one of three technologies selected to be demonstrated as part of the first Air Traffic Management (ATM) Technology Demonstration (ATD-1) [3].

The midterm national airspace system will not include advanced communication methods such as controller-pilot data link communications which could be used to send IM clearances and detailed information about the target aircraft's intended trajectory. To compensate for the lack of controller-pilot data link communications, the ATD-1 concept of operations describes a midterm implementation of IM that uses radio communications to transmit an IM clearance from air traffic control to the flight deck [4]. Once pilots receive the clearance, they are expected to enter it into on-board avionics. Once all the necessary information is entered and all the constraints are met, the flight crew activates the spacing algorithm and flies the commanded speeds to achieve the designated spacing interval behind the target aircraft at the achieve-by point. Since ATD-1 focuses on a near-term environment, a retrofit solution is seen as the most likely implementation of IM avionics. For ATD-1, this retrofit solution is expected to consist of an Electronic Flight Bag (EFB) interface to facilitate IM clearance entry and a primary field-of-view display that will enable pilots to monitor the IM operation.

One of the challenges imposed by the ATD-1 concept of operations is the communication of complex clearances that contain an achieve-by waypoint, a spacing interval, and required information about the target aircraft's route. Due to avionics communication constraints that exist aboard certain aircraft, pilots may be required to enter additional information such as their own aircraft's route, destination airport and descent forecast winds. To support pilots when entering the required information, it is necessary to ensure that the interface is designed to minimize both the time required to input information and the potential for errors. Likewise, it is important for pilots to have adequate information to monitor the spacing operation.

## 2 Background

Previous research conducted by Eurocontrol, MITRE, and NASA investigated both forward-fit and retrofit IM displays. Eurocontrol investigated an IM implementation where IM symbology was integrated into existing cockpit displays [5–8]. In their final implementation the autothrottles automatically adjusted the aircraft’s speeds to match the IM commanded speed. The aircraft displays included IM annunciation on the primary flight display, the target aircraft highlighted on the navigation display, and an IM graphical trend indicator shown on the navigation display. The IM trend indicator displayed current and required spacing, spacing trend and closure rate, and tolerance margins.

MITRE conducted a series of human-in-the-loop experiments to evaluate a retrofit IM implementation that used both an EFB interface in the forward field-of-view and an ADS-B Guidance Display (AGD) to present numerical data in the primary field-of-view [9,10]. More recently, MITRE incorporated IM into a Cockpit Display of Traffic Information (CDTI) that was developed to support multiple ADS-B applications [11].

NASA investigated an IM application where IM symbology was integrated into existing cockpit displays [12–16]. The IM symbology was located on the primary flight display, the navigation display, the multi-function control display unit, and the engine-indicating and crew-alerting system. The symbology on the primary flight display included the IM commanded speed displayed at the top of the speed tape and a green IM speed bug on the speed tape that was designed to indicate the difference between the IM commanded speed and the aircraft’s speed. When the green IM speed bug was used in conjunction with the normal aircraft speed-trend indicator, the pilots could determine if the aircraft was matching the deceleration rate predicted by the IM algorithm. Pilots were notified of new IM speed commands by a solid green box that appeared around the IM commanded speed for a time period of ten seconds. In addition to the symbology on the primary flight display, the IM aircraft was highlighted on the navigation display and multiple alerts and warnings were presented on the engine-indicating and crew-alerting system. The flight crews used the multi-function control display unit to auto-load information from IM clearances provided through controller-pilot data link communications. In addition, one of the human-in-the-loop experiments used an exploratory scenario to investigate a spacing “conformance box” that surrounded the ownship symbol on the navigation display, and was designed to indicate the limits of the current spacing error [15].

After NASA investigated integrated IM displays, there was considerable interest in designing and examining retrofit IM displays in preparation for the ATD-1 flight demonstration. NASA designed IM displays that consisted of an EFB interface for data entry and an auxiliary display in the primary field-of-view for monitoring the IM operation [17–19]. The EFB interface contained data entry fields, a cockpit display of traffic information, and various pieces of IM information required to monitor the IM operation. The auxiliary display was similar to the numerical AGD pre-

sented later in this paper, and was used to present critical IM information in the primary field-of-view. The work described in this paper compares the previously used auxiliary display with a new graphical AGD to determine the usability and acceptability of both implementations, and examines the acceptability of two different EFB interfaces.

## 3 Experiment Design

### 3.1 Experiment Procedure and Scenario Design

#### 3.1.1 Scenario Design

This study investigated the acceptability and usability of retrofit IM displays, while conducting IM operations into Phoenix Sky Harbor airport. Each scenario contained four IM aircraft and eighteen non-IM aircraft arriving on the EAGUL5 and KOOLY5 arrivals to runways 25L or 26. The IM and target aircrafts' routes always shared a common runway; however, they did not necessarily share a common arrival. During each scenario, two of the IM and target aircraft pairs began on the same arrival, and the remaining two pairs began on different arrivals. Within each scenario, the IM aircraft began approximately five minutes prior to top-of-descent and flew until landing. Within this time, pilots were required to enter information about their aircraft's trajectory into the IM avionics, receive an IM clearance and enter the appropriate data into the IM avionics, activate the IM algorithm, and fly the IM commanded speeds to achieve a precise spacing interval behind the target aircraft at the final approach fix.

The scenarios were designed to simulate a midterm airspace environment where IM clearances were provided via radio communications and pilots manually entered the IM clearance information and the ownship's intended trajectory into the IM avionics. To increase the realism of the scenarios, confederate air traffic controllers provided realistic voice communications to the IM aircraft and to the other eighteen aircraft in the airspace. Additionally, winds observed at Phoenix Sky Harbor Airport were used as the truth winds and a temporally offset wind field was used as the wind forecast.

This study investigated the data entry task and the task of monitoring the IM operation during normal operations. As such, the scenarios within this experiment were scripted so that all of the aircraft were given achievable spacing clearances and the IM aircraft were expected to conduct uninterrupted IM operations to the final approach fix. A prior IM experiment conducted at NASA LaRC investigated various scenarios that required the flight crew to suspend or terminate an IM operation before reaching the achieve-by point [17, 18].

### **3.1.2 Experiment Procedure**

Two groups, each consisting of eight active airline pilots, participated in this experiment. Each group was present for a two day period. During this time, they received training and conducted eight data collection runs. The subject pilots completed post-run surveys, an extensive post-experiment survey, and participated in a post-experiment group debrief. Each group of eight pilots was split into four two-person crews, each consisting of a captain and first officer. Throughout the experiment the subject flown aircraft were rotated between four different sets of initial conditions and the treatment conditions were randomly ordered. To mitigate learning and fatigue effects, individual pilots within each two person crew switch roles from pilot flying to pilot monitoring, or vice versa, after each run.

Comprehensive classroom sessions as well as four training scenarios were provided to the participants to familiarize them with the IM procedures and displays, and to help them acclimate to the simulators. Once the training was complete, each group of pilot participants flew eight data collection runs.

Both quantitative and qualitative data were collected during each of the data collection runs. The quantitative data consisted of aircraft state data and algorithm performance data for each IM aircraft. The qualitative data were collected from electronic post-run surveys (Appendix A) completed after each data collection run, an extensive post-experiment survey (Appendix B), and a group post-experiment debrief session. The qualitative data included measures of pilot workload and usability and acceptability ratings of the IM displays.

### **3.1.3 Participants**

The pilots who participated in this study were all active airline pilots with glass cockpit experience. The pilots' ages ranged from 44 to 65 years, and they had an average of 13,600 hours of commercial flight experience. In order to ensure that the pilots were able to use their normal crew procedures, each two person flight crew consisted of a captain and first officer from the same airline.

## **3.2 Pilot Tasks**

Within this study, there were three major tasks related to the IM operation: entering the IM aircraft's trajectory intent information into the IM avionics, receiving an IM clearance and entering the necessary information into the IM avionics, and flying the speeds commanded by the IM avionics to achieve a precise spacing interval at the final approach fix.

During cruise, the flight crews were responsible for entering information about their aircraft's intended trajectory into the IM avionics. This information was required to be manually entered because it was assumed that a limited amount of the information from the flight management system would be available to the retrofit IM application.

As a result, pilots entered their aircraft's cruise speed, cruise altitude, the speed at which they were expected to transition from Mach to calibrated airspeed, their destination airport, and their aircraft's route. Additionally, pilots were required to manually enter their aircraft's descent forecast winds. Both of the data entry interfaces examined in this experiment contained several selectable elements to help streamline the data entry process.

Air traffic control provided the flight crews with an IM clearance before the aircraft crossed 30,000 ft. If the target and IM aircraft were on the same arrival, air traffic control issued a "when able" clearance, instructing the flight crews to activate the interval management clearance as soon as they entered the necessary information. Alternatively, when the IM and target aircraft were on different arrivals, air traffic control provided the flight crew with a clearance instructing them to activate the IM operation when they entered the Terminal Radar Approach Control (TRACON) airspace. After receiving the IM clearance, the pilot monitoring was expected to enter the spacing goal, target aircraft ID, and the target aircraft's route into the EFB interface. After the data was entered and the pilot flying had crosschecked the information, the flight crew activated the IM avionics at the proper time; either at the designated waypoint if the IM and target aircraft were on different routes or immediately if the IM and target aircraft were on the same route. Once IM was activated and the IM avionics had all the necessary information to compute valid speed guidance, a commanded speed was displayed on the primary field-of-view display.

When IM was activated and speed guidance was displayed, the flight crews were required to verify that the speed was safe to fly and then enter it into the Mode Control Panel (MCP) speed window. As the commanded speed changed, pilots were required to verify that each new commanded speed was safe to fly and update the speed in the MCP speed window in addition to carrying out their normal tasks. When the IM aircraft reached the final approach fix, the pilots slowed to their landing speed and prepared for landing. If the flight crew did not think the speed was safe to fly or they were not comfortable flying it at any point during the flight, they had the option of contacting air traffic control and canceling the IM operation.

### **3.3 Data Entry Interface**

This experiment examined two different EFB interfaces that pilots used to enter information into the IM avionics. The first interface, which will be referred to as the menu-entry EFB interface, contained separate pages for each new piece of data that had to be entered. The second interface, which will be referred to as the multi-entry EFB interface, enabled pilots to enter multiple pieces of data on a single page. Since it was assumed that a limited amount of the information from the flight management system would be available to the retrofit IM application, pilots were required to enter ownship trajectory intent information and the descent forecast winds in addition to the IM clearance (table 2). It is likely that this is a worst-case data entry scenario.

The ownship trajectory intent data that pilots were required to enter were the IM aircraft’s cruise altitude, cruise Mach, the transition between Calibrated Airspeed (CAS) and Mach, the IM aircraft’s destination airport, and the IM aircraft’s route. In addition to the airport, pilots were required to enter the altitude, speed, and direction for a set of four descent forecast winds. Lastly, pilots were required to enter the following data from the spacing clearance: the spacing goal assigned by air traffic control, the target aircraft’s Identification (ID), and the target aircraft’s intended route. The achieve-by waypoint and terminate waypoint were automatically set as the final approach fix to conform with the ATD-1 concept of operations [4]; however, the pilots could override the pre-populated value if desired.

The main CDTI page of both EFB interfaces contained certain symbology designed to improve pilots’ situational awareness of the IM operation (figures 1 and 5). First, the target aircraft was highlighted in green on the CDTI and the data block of the target aircraft was expanded to include the target aircraft’s ID. Secondly, there were two cyan boxes added to the lower portion of the main CDTI pages. The top box contained text that indicated the IM mode and the target aircraft’s ID. The IM mode indicator displayed modes that indicated the spacing algorithm was either actively spacing, suspended, unable to compute a speed, or waiting for various constraints to be met before providing a commanded speed. The mode appeared as green text when in spacing mode and as white text when in any other mode. The bottom cyan box displayed IM status messages when the IM or target aircraft were not on the expected route, if the target aircraft’s ADS-B signal was lost, or if there was another problem that prevented the IM algorithm from providing speed guidance.

Table 2: Data Pilots were required to enter

**Ownship Data:**

- Cruise Altitude
- Cruise Mach
- Descent Mach/CAS
- Descent forecast winds
- Destination airport
- Ownship route<sup>1</sup>
  - Arrival<sup>1</sup>
  - Transition<sup>1</sup>
  - Approach<sup>1</sup>
  - Approach Transition<sup>1</sup>

**Spacing Clearance Data:**

- Achieve-by waypoint<sup>3</sup>
- Terminate waypoint<sup>3</sup>
- Spacing goal
- Target aircraft ID<sup>2</sup>
- Target aircraft route<sup>1</sup>
  - Arrival<sup>1</sup>
  - Transition<sup>1</sup>
  - Approach<sup>1</sup>
  - Approach Transition<sup>1</sup>

---

<sup>1</sup>Pilots were able to select these items from a list of options instead of manually typing the information.

<sup>2</sup>In the menu-entry EFB interface, the target aircraft’s ID could be selected from a list of options if the target aircraft was within ADS-B range when the pilot was entering the IM clearance information. Otherwise the target aircraft’s ID had to be manually typed in.

<sup>3</sup>These fields were automatically populated with the final approach fix. Pilots could select a different waypoint from a list of options if desired, but they were not required to do so for this experiment.

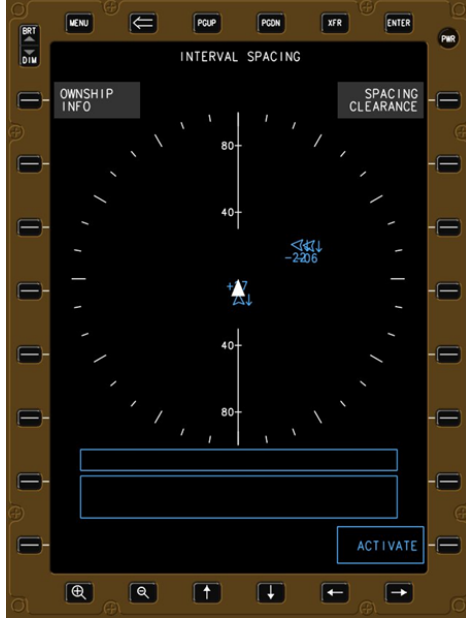


Figure 1: Menu-entry EFB display CDTI page

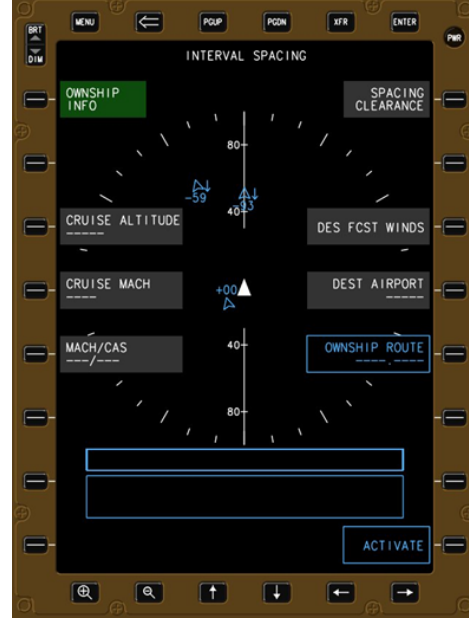


Figure 2: Menu-entry EFB display data input menu

### 3.3.1 Menu-Entry

The menu-entry EFB interface is roughly based off of the EFB interface used in a previous human-in-the loop experiment [17, 18]. Since ownship trajectory data may not be available from the flight management system of all aircraft, modifications were made to the interface that enabled pilots to directly enter their aircraft's trajectory intent information into the IM avionics. Additional modifications included the removal of the scheduled time of arrival functionality and the addition of the terminate waypoint field to improve conformance with the minimum operational performance requirements that are in the process of being developed. The revised EFB interface required pilots to manually enter several additional pieces of information, increasing the workload associated with the data entry task.

The menu-entry EFB interface contains two menus that the pilot can select from the main page (figure 1). Pressing the OWNSHIP INFO button activates a menu that shows all of the data entry fields for ownship data (figure 2). Similarly, pressing the SPACING CLEARANCE button shows all of the data entry fields for IM clearance data. These two menus were designed to prevent confusion by separating the ownship data from the IM clearance data. Pressing any of the data entry fields switched the interface to a data entry page, which was either a text entry page that allowed pilots to manually type in information or a page that allowed pilots to select the desired parameter from a list of options. Figure 4 is an example of a text input page and figure 3 is an example of the route selection page.

When all necessary data were entered, the ACTIVATE button on the bottom right of the main CDTI page switched from inactive to active. At that time, the other





Figure 3: Menu-entry EFB display CDTI page

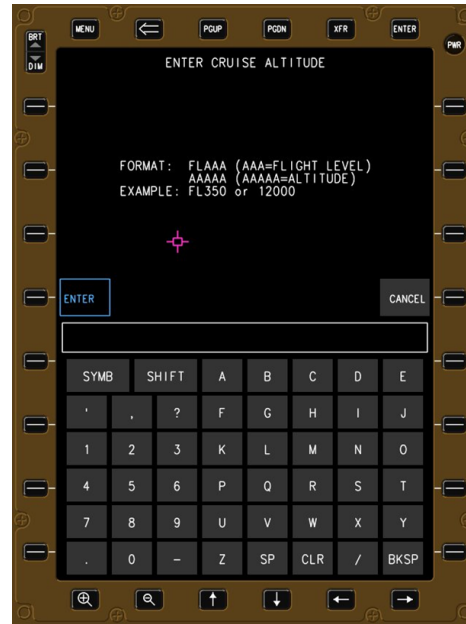


Figure 4: Menu-entry EFB display data input menu

pilot could easily cross-check the information that was entered by selecting either the ownship data menu or the spacing clearance menu. Once all of the information was crosschecked, pilots pressed the ACTIVATE button to activate the IM algorithm.

### 3.3.2 Multi-Entry

The difference between the multi-entry and menu-entry EFB pages was that the multi-entry interface allowed multiple pieces of data to be entered on a single page, as opposed to a single entry on each page on the menu-entry EFB pages. To simplify the interface design most of the selection pages were identical to those used in the menu-entry interface. To enter data into the IM avionics, pilots pressed the INTERVAL SPACING button on the main CDTI page (figure 5), bringing them to a series of data entry pages.

The top half of each data entry page contained multiple data entry fields, and the bottom half of each page contained a keyboard (figure 6). When pilots were entering text data, they pressed one of the data entry fields, causing a cursor to appear in the data entry field and enabling the pilots to type in the appropriate data. To enter selectable data, the pilots pressed the data selection button, which brought them to the appropriate data selection page. After the information was selected, the interface returned to the main data entry page. The data selection pages used in the multi-entry EFB interface were identical to the data selection pages used in the menu-entry EFB interface.

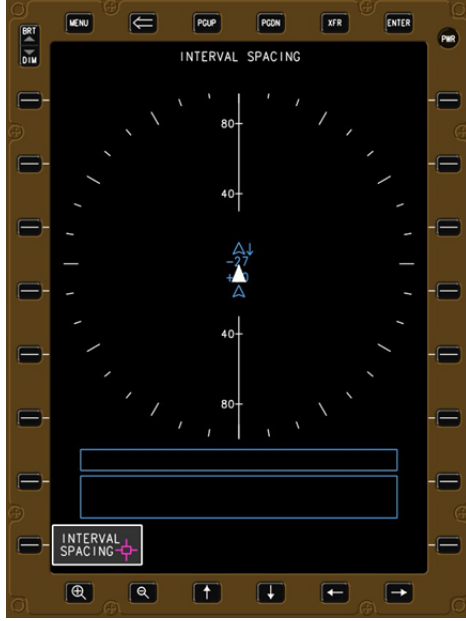


Figure 5: Multi-entry EFB display CDTI page



Figure 6: Multi-entry EFB display data input page

When pilots had finished entering data into a particular page, they could move to the next data entry page by pressing the PAGE button. At any time in the data entry process, the pilot could press the EXIT button to clear all of the data they had entered and return to the main CDTI page. The pilots could also press the SAVE & EXIT button to save all of the data they had entered and return to the main CDTI page. Once all required information was entered, the ACTIVATE button became selectable, enabling pilots to activate the IM operation.

### 3.4 Primary Field-Of-View Displays

Two primary field-of-view displays were investigated in this experiment. The first display, which will be referred to as the numerical AGD, is similar to a display that has been used in several IM experiments and flight tests [9, 10, 17–20]. The numerical AGD contained three fields that could only display numbers and a green Light-Emitting Diode (LED) indicator (figure 7). The second display, which will be referred to as the graphical AGD, contained two graphical indicators and text information that were unable to be displayed on the numerical AGD (figure 8).

#### 3.4.1 Numerical AGD

The numerical AGD displayed three values, which are shown in figure 7: the IM commanded speed (feature 1), a fast/slow indicator (feature 2), and the spacing error (feature 3). The far



Figure 7: Numerical AGD

left indicator displayed the IM commanded speed that pilots were expected to dial into the aircraft's MCP speed window to close the control loop. When the IM commanded speed changed, the LED light in the top left corner of the numerical AGD illuminated until the new commanded speed was dialed into the MCP speed window (feature 4). The middle indicator was a fast/slow indicator that showed pilots the difference between the IM aircraft's speed and the speed commanded by the spacing algorithm. A positive value indicated that the aircraft was too fast and a negative value indicated that the aircraft was too slow relative to the IM commanded speed. The field on the far right showed the predicted spacing error at the final approach fix. The spacing error was computed by determining the difference between both aircrafts' estimated times of arrival, assuming that they would fly the published speeds to the achieve-by point, and subtracting the spacing interval assigned by air traffic control. A positive spacing error indicated that the IM aircraft was projected to have a larger spacing interval at the achieve-by point than the assigned spacing goal (a late arrival), and a negative spacing error indicated that the aircraft was projected to have a smaller spacing interval at the achieve-by point (an early arrival).

### 3.4.2 Graphical AGD

The graphical AGD was a three inch by three inch glass display that enabled graphical trend indicators and text data to be presented in the primary field-of-view. The graphical AGD contained a fast/slow indicator, the IM commanded speed, the IM mode, the target aircraft's ID, an IM progress indicator, and a space for status messages (figure 8).

A graphical fast/slow indicator was displayed on the leftmost section of the graphical AGD (feature 1). The fast/slow indicator consisted of three white diamonds spaced 20 knots apart and a square green bug, and showed the aircraft's speed deviation from the IM commanded speed. To support the pilot task of maintaining a speed within ten knots of the IM commanded speed, the numeric speed deviation was displayed inside the green box when the speed deviation was greater than ten knots. An acceleration arrow was added to the fast/slow indicator to enable the pilots to determine whether they were trending toward the commanded speed. The tip of the acceleration arrow showed the projected speed deviation in ten seconds if the aircraft's acceleration and the acceleration predicted by the spacing algorithm remained the same.

The middle column of the graphical AGD contained the IM commanded speed (feature 2), an IM mode indicator (feature 3), and the target aircraft's Id (feature 4). The IM speed was displayed in large green numbers, which would be shown in reverse video when the IM commanded speed changed (black characters on a green



Figure 8: Graphical AGD

background), notifying pilots to dial the new IM speed into the MCP speed window. Once the pilots dialed the IM speed into the speed window, the IM speed indicator would return to its normal state. The IM mode indicator displayed modes that indicated that the spacing algorithm was either actively spacing, suspended, unable to compute a speed, or waiting for various constraints to be met before providing a commanded speed to the flight crew. The mode appeared as green text when the aircraft was actively spacing and as white text when in any other mode. Whenever the mode changed, a solid green box appeared around the mode indicator for a time period of ten seconds. The target aircraft's ID was displayed below the IM mode indicator, and was shown using text that matched the color of the IM mode.

The rightmost column of the graphical AGD contained an IM progress indicator. This indicator was intended to provide pilots with extra situational awareness of the IM operation by showing them the IM aircraft's spacing error in relation to the IM feasibility bounds. The indicator was displayed using a long vertical white line with tick marks at the top, middle, and bottom. The top and bottom ends of the progress indicator showed the IM feasibility bounds, which were approximated as  $\pm 10$  percent of the IM aircraft's time-to-go. A green triangle indicated the spacing error in relation to the IM feasibility bounds. The spacing error was computed by determining the difference between both aircrafts' estimated times of arrival with the assumption that they would fly the published speeds to the achieve-by point, and subtracting the spacing interval assigned by air traffic control. The assigned spacing interval was no longer reachable when the green triangle was at the top or bottom of the indicator, informing the flight crew that the spacing algorithm did not have enough control authority to achieve the assigned spacing goal. When this occurred, a message was displayed on the graphical AGD directing the flight crews attention to the EFB interface, which displayed a message that explained that the spacing goal was no longer achievable.

The last pieces of information displayed on the graphical AGD were two status messages shown in the blank space below the other symbology (feature 6). There were two status messages that could be displayed: DRAG REQ and EFB MSG. The DRAG REQ message was displayed when the aircraft's speed was more than ten knots higher than and diverging from the IM commanded speed. The EFB MSG symbology was used to direct the pilot's attention to a larger message box on the EFB display, where more detailed messages were displayed.

## **3.5 Facilities**

### **3.5.1 Simulators**

This experiment was conducted in the Air Traffic Operations Laboratory at NASA LaRC. This facility contains a number of desktop aircraft simulators, air traffic control stations, and pseudo pilot stations. Each of the simulation platforms can be used together to simulate complex air traffic operations.



Figure 9: Dual crew desktop simulator displays

All of the pilots who participated in this experiment flew dual crew desktop simulators that emulated a large transport aircraft. Each simulator contained a high fidelity six degree of freedom dynamics model and aircraft displays shown on three 27 inch touchscreen monitors (figure 9). Pilots interacted with the desktop simulators through either a mouse or touchscreen interface. Each simulator contained displays and systems found on large transport aircraft, including right and left primary flight displays, right and left navigation displays, right and left EFBs, a flight management system, auto-throttles, radios, and ADS-B in/out. In addition to normal aircraft systems, retrofit IM avionics were emulated by the desktop simulators. New pages that were added to the EFB interface enabled pilots to enter information into the IM avionics. Information from the IM avionics was displayed on the EFBs and on two auxiliary IM displays located above the right and left primary flight displays.

### Spacing Algorithm

The spacing algorithm used in this experiment was a trajectory based algorithm developed at NASA LaRC, known as the eleventh version of the Airborne Spacing for Terminal Arrival Routes (ASTAR-11) spacing algorithm [21]. The spacing algorithm used speeds from the published standard terminal arrival route along with the IM and target aircrafts' intended routes to compute their estimated times of arrival at a designated point in space, referred to as the achieve-by point. The estimated times of arrival for the IM and target aircraft were used in conjunction with the spacing goal to calculate the spacing error. Once the spacing error was calculated, proportional control was used to compute the amount of speed compensation that the IM aircraft needed to null the spacing error by the achieve-by point. The speed compensation was added to the published speeds, quantized into discrete increments, and displayed to the flight crew. Since this study investigated a retrofit IM implementation, the pilots were required to close the control loop by entering the IM commanded speeds into the MCP speed window.

### 3.6 Experiment Design and Independent Variables

Each scenario in this experiment was split into two flight segments: entering the IM clearance and monitoring the IM operation. To enable the investigation of EFB displays and primary field-of-view displays, these two segments of flight were assumed to be independent from each other, and the performance metrics were carefully

selected to pertain to only one segment of flight. Each group of pilots conducted two replicates of four distinct scenarios—one with the captain flying and the other with the first officer flying (tables 3 and 4).

Table 3: Experiment design during data entry phase of flight

	<b>EFB Displays</b>	
	<b>Menu-entry</b>	<b>Multi-entry</b>
<b>Out of ADS-B Range</b>	First Officer Flying Captain Flying	First Officer Flying Captain Flying
<b>In ADS-B Range</b>	First Officer Flying Captain Flying	First Officer Flying Captain Flying

Table 4: Experiment design when monitoring IM

	<b>Primary Field-Of-View Displays</b>	
	<b>Numerical AGD</b>	<b>Graphical AGD</b>
<b>Nominal</b>	First Officer Flying Captain Flying	First Officer Flying Captain Flying
<b>Perturbation</b>	First Officer Flying Captain Flying	First Officer Flying Captain Flying

The independent variables associated with the data entry phase of flight were the previously discussed EFB displays and whether the target’s ADS-B information was available when IM was initiated (table 3). During each scenario two out of the four target aircraft began on a different arrival than the IM aircraft and were out of ADS-B range when IM operations began. The remaining two target aircraft began on the same route as the IM aircraft and thus were within ADS-B range when the IM operation began. On the menu-entry interface, pilots were able to select the target aircraft’s ID from a list when it was in ADS-B range. If the target was not in ADS-B range when the IM clearance was entered, pilots were required to type in the target aircraft’s ID. On the multi-entry interface, pilots were always required to manually type in the target aircraft’s ID regardless of whether the target aircraft was in ADS-B range.

The independent variables associated with conducting IM operations were the previously described primary field-of-view displays and the target aircraft’s deviation from its expected speeds (table 4). During the nominal cases the target aircraft flew their published speeds, which matched the speeds that the spacing algorithm predicted. During the perturbation cases, the target aircraft was slowed below the published speeds between TRACON entry and the start of final approach. This caused the spacing error on the graphical AGD progress indicator to increase until it was close to the early feasibility bound and the spacing error on the numerical AGD to increase in value.

### 3.7 Experiment Limitation

A limitation of this study that the reader should be aware of is that this study was performed using desktop computer simulators instead of a flight simulator cab. While this does not reduce the importance of the findings, this limitation should be taken into account when interpreting the data. Particularly, certain metrics, such as the pilot’s reaction time to new IM commanded speeds, should only be used for comparison purposes within this experiment.

## 4 Results: Data Entry Phase of Flight

### 4.1 Pilot Workload

The pilot participants used the Modified Cooper-Harper (MCH) workload scale to rate their workload level when entering IM information into the EFB interfaces. The MCH workload scale contains a flowchart that the pilot participants followed to determine their workload level [22]. A workload level of one indicated that the task was very easy and a workload level of ten indicated that the task was impossible. For the purposes of this study, ratings of one to three were considered acceptable responses. Overall, the mean pilot workload rating when using the menu-entry EFB interface was 2.0 ( $SD=0.9$ ,  $N=64$ ), and the mean workload rating when using the multi-entry EFB interface was 2.3 ( $SD=1.4$ ,  $N=64$ ). The pilot workload ratings were less than three on the MCH rating scale ( $p<0.0005$ ), indicating that the workload was acceptable. A series of Wilcoxon signed rank tests with Bonferroni adjustment revealed no statistically significant interaction effects between the EFB interfaces and whether the target aircraft ADS-B information was available when IM information was entered. Additionally, there was no difference between the mean workload when pilots used the menu-entry EFB and the multi-entry EFB interface ( $p=0.074$ ), or the workload for aircraft that began within or out of ADS-B range of their target aircraft ( $p=0.697$ ).

### 4.2 Acceptability of Data Entry Time

One metric of considerable importance was the acceptability of the time it took pilots to enter all of the data into the EFB interface. The data entry task examined in this experiment assumed limited connectivity between the IM aircraft’s flight management system and the IM avionics where pertinent information is not available to the IM application, and is seen as a worst-case scenario. One goal of this study was to determine whether the worst-case data entry task was acceptable to pilots for the ATD-1 flight demonstration or whether increased connectivity between the flight management system and IM avionics was required.

Pilots were asked to rate whether the amount of heads-down time required to enter information into the EFB interface was acceptable using a seven-point scale ranging from one (completely agree) to seven (completely disagree)(figure 10). The mean

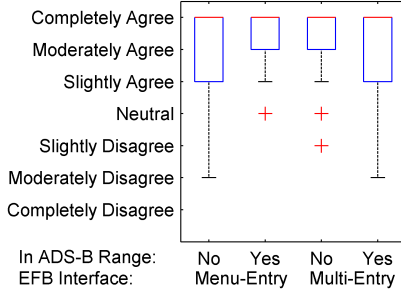


Figure 10: Pilot ratings describing whether they agreed that the amount of data entry was acceptable

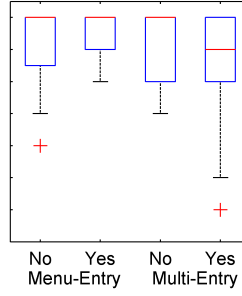


Figure 11: Pilot ratings describing whether they agreed that the EFB interface was intuitive

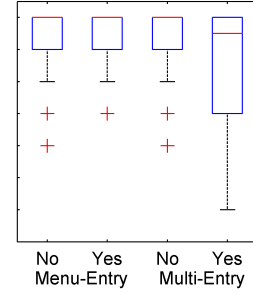


Figure 12: Pilot ratings describing whether they agreed that the EFB interface was acceptable

rating of the menu-entry EFB interface was 6.1 ( $SD=1.2$ ,  $N=64$ ), and the mean rating for the multi-entry EFB interface was 5.9 ( $SD=1.5$ ,  $N=64$ ). Overall, the mean acceptability ratings were statistically significantly higher than 4.5 ( $p \leq 0.0005$ ), indicating that the amount of heads down time needed to input the data into the EFB was acceptable. A series of Wilcoxon signed rank tests with Bonferroni adjustment revealed no interaction effects between the EFB interfaces and whether the target aircraft ADS-B information was available when IM information was entered. In addition, there was no difference between the mean acceptability of the menu-entry and multi-entry EFB interfaces ( $p \leq 0.315$ ), or the acceptability for aircraft that began within or out of ADS-B range of the target aircraft ( $p \leq 0.880$ )

### 4.3 Intuitiveness

Pilots were also asked to rate the intuitiveness of the EFB interfaces using a seven-point scale ranging from one (completely disagree) to seven (completely agree) that the IM EFB interfaces were intuitive (figure 11). The mean intuitiveness rating of the menu-entry EFB interface was 6.3 ( $SD=1.0$ ,  $N=64$ ), and the mean intuitiveness rating for the multi-entry EFB interface was 5.8 ( $SD=1.6$ ,  $N=64$ ). For each of the four treatment combinations, the mean intuitiveness ratings were statistically significantly higher than 4.5 ( $p \leq 0.009$ ), indicating that pilots found entering the IM clearance information into the EFB to be easy and intuitive. A series of Wilcoxon signed rank tests with Bonferroni adjustment revealed a statistically significant difference between the pilot intuitiveness ratings for the menu-entry and multi-entry EFBs when the target aircraft was within ADS-B range. Pilots rated the menu-entry EFB as more intuitive than the multi-entry EFB. There were no statistically significant differences between any of the other treatment combinations.



#### 4.4 Frustration Associated with the EFB Interfaces

Pilots were also asked to rate their frustration associated with the use of the EFB interfaces using a seven-point scale ranging from one (completely disagree) to seven (completely agree) that entering information into the EFB resulted in a minimal amount of frustration (figure 12). The mean frustration rating of the menu-entry EFB interface was 6.3 ( $SD=1.0$ ,  $N=64$ ), and the mean acceptability rating for the multi-entry EFB interface was 5.8 ( $SD=1.6$ ,  $N=64$ ). For each of the four treatment combinations, the mean ratings were significantly higher than 4.5 ( $p \leq 0.005$ ), indicating that pilots found entering the IM clearance information into the EFB to result in a minimal amount of frustration. A series of Wilcoxon signed rank tests with Bonferroni adjustment revealed a statistically significant difference between the data entry ratings for the menu-entry and multi-entry EFB interfaces when the target aircraft was within ADS-B range. Pilots rated the menu-entry EFB as less frustrating ( $M=6.5$ ,  $SD=0.7$ ) than the multi-entry EFB ( $M=5.5$ ,  $SD=1.9$ ). There were no statistically significant differences between any of the other treatment combinations.

#### 4.5 General Pilot Comments

Comments from the post-experiment survey and the post-experiment debrief revealed that a majority of pilots thought that the data entry required would be acceptable, but not ideal. Overall, 15 out of the 16 pilot participants rated the menu-entry EFB interface as minimally acceptable and 14 out of the 16 pilot participants rated the multi-entry interface as minimally acceptable.<sup>4</sup> One of the pilots rated both EFB interfaces as unacceptable and desired an interface that merged the ability to enter multiple pieces of information on a single page with a more intuitive layout. He also thought that the multi-entry interface should enable pilots to type information into a scratch-pad and then select the appropriate data-entry field instead of selecting the appropriate data entry field and then typing in the data, increasing conformance with current multi-function control units. Comments provided in the post-experiment debrief indicated that both interfaces were minimally acceptable, but pilots highly preferred the menu-entry interface over the multi-entry interface. The pilot participants stated that they felt that menu-entry interface was a lot more intuitive and acceptable than the multi-entry interface. The reasons for this included less intuitive page navigation on the multi-entry EFB interface and wind entry fields mismatched with the descent forecast winds displayed on the aircraft's multi function control unit. Lastly, the pilots commented that they thought the amount of data they were required to enter was very high. To reduce workload and increase acceptability when entering ownship data, it is recommended that future EFB interfaces enable pilots to auto-load their descent forecast winds. Other methods of decreasing the amount of data entry, such as increasing communication between the flight management system and the IM avionics, could also be considered.

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<sup>4</sup>Pilots were asked about minimal acceptability to determine whether the proposed displays and amount of data they were required to enter would be acceptable for the ATD-1 flight demonstration.

There was also a less than ideal interaction between the interface and procedures that was observed throughout the simulation. Within this simulation, pilots were provided two types of IM clearances. “When able” IM clearances were provided when the IM and target aircraft were on the same route, and “at” clearances were provided when the IM and target aircraft were on different routes, instructing them to activate the IM equipment when their aircraft crossed the meter fix (when they entered the TRACON). When pilots received an “at” clearance, they were instructed to draw a circle around the activation waypoint on their navigation display as a reminder to activate the IM avionics when they crossed the activation waypoint. Despite all of the training provided, several pilots attempted to override the prepopulated achieve-by or terminate waypoints with the activation waypoint. Often times, this behavior was caught by the other pilot and corrected; nevertheless, this behavior continued throughout the experiment. To solve this problem, the procedures could be modified or a new data field for the activation waypoint could be added to the interface.

## 5 Results: Monitoring Phase of Flight

### 5.1 Pilot Acceptability and Workload

The primary data collected during the monitoring phase of flight were pilot ratings of the usefulness and acceptability of the displays. The objective of these ratings was to evaluate the acceptability of the graphical and numerical AGDs, and determine if one was more acceptable than the other. To examine the acceptability and usability of the displays, pilots were asked a series of questions in the post-run and post-experiment surveys. Additional information was gathered during a post-experiment debrief.

#### 5.1.1 Pilot Workload and Situational Awareness

The pilot participants used the MCH workload scale to rate their workload level when conducting IM operations into Phoenix Sky Harbor Airport. For the purposes of this study, ratings of one to three were considered acceptable responses. Overall, the mean pilot workload rating when using the numerical AGD was 2.6 ( $SD=1.4$ ,  $N=64$ ), and the mean workload rating when using the graphical AGD was 1.9 ( $SD=1.5$ ,  $N=64$ ). During the monitoring phase of flight, the mean workload ratings were 3 or less on the MCH rating scale ( $p < 0.015$ ), indicating that the workload was acceptable. A series of Wilcoxon signed rank tests with Bonferroni adjustment revealed no statistically significant interaction effects between the primary field-of-view displays and the target aircraft’s deviation from its expected speeds. Although the mean workload rating was higher when using the numerical AGD than the graphical AGD, the difference was less than one unit on the MCH rating scale ( $p = 0.010$ ), indicating the display used had a relatively small operational impact on workload.

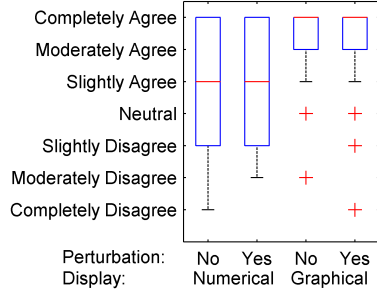


Figure 13: Pilot ratings describing whether they agreed that the IM displays provided adequate situational awareness

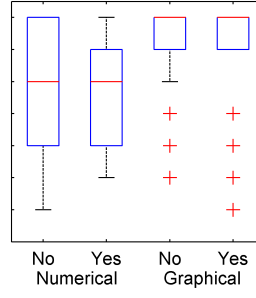


Figure 14: Pilot ratings describing whether they agreed that the IM displays were intuitive

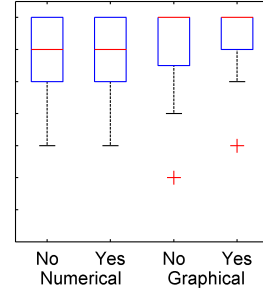


Figure 15: Pilot ratings describing whether they agreed that the IM commanded speeds made sense to them

The pilot participants were also asked to rate whether they agreed that the IM displays provided adequate situational awareness using a seven point Likert scale ranging from one (completely disagree) to seven (completely agree) that the displays provided adequate situational awareness (figure 13). The mean rating provided when using the numerical AGD was 5.0 ( $SD=1.9$ ,  $N=64$ ), and the mean rating provided when using the graphical AGD was 6.1 ( $SD=1.5$ ,  $N=64$ ). A series of Wilcoxon signed rank tests with Bonferroni adjustments revealed a statistically significant difference between the mean situational awareness ratings for the graphical AGD when a perturbation occurred and the numerical AGD without a perturbation. For the treatment combinations with the numerical AGD with a perturbation, and the graphical AGD both with and without a perturbation, the mean ratings were 4.5 or higher, indicating that the primary field-of-view displays provided adequate situational awareness. However, for the scenario with the AGD without a perturbation, the mean rating was not statistically significantly higher than 4.5.

### 5.1.2 Intuitiveness of Displays

Pilots were also asked to rate the intuitiveness of the displays using a seven-point Likert scale ranging from one (completely agree) to seven (completely disagree) that the IM displays were intuitive (figure 14). The mean intuitiveness rating of the scenarios that used the numerical AGD was 4.9 ( $SD=1.8$ ,  $N=64$ ), and the mean intuitiveness rating for the scenarios that used the graphical AGD was 6.2 ( $SD=1.4$ ,  $N=64$ ). For all four treatment combinations, the mean intuitiveness ratings were 4.5 or higher, indicating that the primary field of view displays were intuitive. A series of Wilcoxon signed rank tests with Bonferroni adjustment revealed that the mean intuitiveness ratings for the graphical AGD when a perturbation occurred was significantly higher than the numerical AGD both with and without a perturbation.

### 5.1.3 Understanding of IM commanded speeds

When creating this study, it was hypothesized that the graphical IM progress indicator may increase the pilots' understanding of the commanded speeds. For instance, when the progress indicator indicated the aircraft was projected to arrive early, the IM aircraft should be commanded a speed below the nominal profile. Conversely, when the progress indicator showed the aircraft was projected to arrive late, the IM aircraft should be commanded a speed above the nominal profile. Additionally, when the spacing error was returning to zero, the commanded speed should trend toward the nominal speed profile. It should be noted that these behaviors are highly dependent on the particular spacing algorithm used in this experiment, and should not be generalized to all spacing algorithms.

Pilots were asked to use a seven point scale to rate whether the IM commanded speeds made sense to them (figure 15). A rating of seven indicated that the pilots completely agreed that the IM speeds made sense to them and a rating of one indicated that the pilots completely disagreed. The mean rating provided when using the numerical AGD was 5.9 ( $SD=1.3$ ,  $N=64$ ), and the mean rating provided when using the graphical AGD was 6.3 ( $SD=1.1$ ,  $N=64$ ). A series of Wilcoxon signed rank tests with Bonferroni adjustment revealed no statistically significant differences in the mean pilot understanding of IM speeds between the numerical AGD and the graphical AGD ( $p = 0.966$ ), or between the perturbation and nominal scenarios ( $p = 0.601$ ). This suggests that the graphical IM progress indicator (the early/late indicator) did not increase the pilots' understanding of the commanded speeds. Pilot comments about the IM progress indicator, which are discussed in the next sections, confirmed that they did not use the IM progress indicator often and that many pilots did not find the information very useful.

### 5.1.4 Usefulness of Symbology on Displays

In the post-experiment survey, pilots were asked to rate the usefulness of display elements on both the numerical AGD and the graphical AGD (figure 16). A majority of pilots rated the IM commanded speed indication, the IM mode indicator, and the target's ID on the graphical AGD as very useful or required for IM. A majority of pilots also rated the usefulness of the fast/slow indicator, the acceleration arrow on the fast/slow indicator, and the IM progress indicator as slightly useful to very useful. The ratings of interface elements on the numerical AGD showed a similar trend. A majority of pilots rated the IM commanded speed as very useful to required for IM, and a majority of pilots rated the fast/slow indicator on the numerical AGD as not useful at all to moderately useful. The usefulness ratings of the IM commanded speed were lower for the numerical AGD than for the graphical AGD. It is suspected that this difference was caused by a lack of saliency of speed change alerting on the numerical AGD.

With the exception of the IM progress indicator, pilot comments during the post-experiment debrief matched the survey data presented in figure 16. A majority of pilots stated that they found the fast/slow indicator along with the acceleration

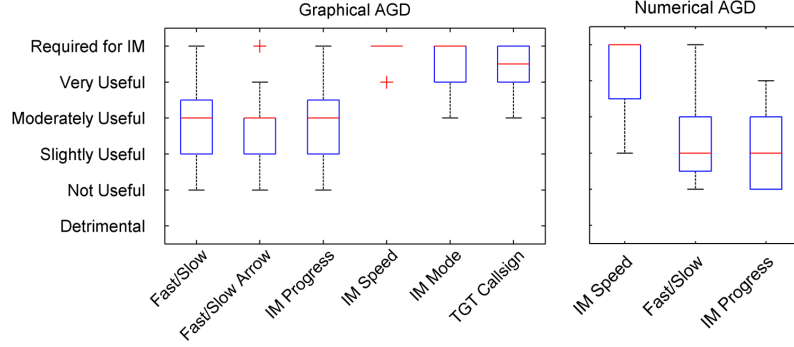


Figure 16: Usefulness ratings of primary field-of-view display symbology

arrow somewhat useful. Despite rating the IM progress indicator as moderately useful, pilots in the post-experiment debrief unanimously stated that they had not used it and did not believe it should be a requirement in future displays. Additionally, none of the pilots had not noticed the large increase in spacing error that occurred during perturbation scenarios, suggesting that they were not consistently monitoring the IM progress indicator when conducting IM operations.

The IM progress indicator used in this experiment did not provide pilots with a compelling reason to use it. The spacing error did not help the pilots better understand the IM commanded speeds, and comments from the post-experiment debrief indicated that the progress indicator did not provide pilots with increased understanding of the IM operation. The spacing error that was computed by the spacing algorithm used in this experiment depended on several factors, which include the target aircraft’s deviation from the published speeds, the IM aircraft’s deviation from its published speeds, and the descent wind forecast error. All of these uncertainties can combine to make the estimated times of arrival unpredictable when the aircraft are far from the achieve-by point, and make it difficult for pilots to understand the reason why a particular IM speed is commanded. Variations within the system can cause the spacing error to increase, only to be nulled later in the arrival, making it difficult for pilots to extract meaningful information from the indicator. Despite these findings, future research could further investigate the results of this experiment by examining IM progress indicators during off-nominal operations and investigating different IM progress indicator designs. It should also be noted that the results from this study may only apply to achieve-by IM operations with the particular trajectory-based algorithm that was used. The usefulness of the IM progress indicator may change if the operation or spacing algorithm are changed.

Overall, pilots preferred the graphical AGD over the numerical AGD. Many pilots thought that the information presented on the graphical AGD was more intuitive than the numerical AGD and that alerting of new IM speed changes was better. The graphical AGD was rated as more intuitive and provided pilots with greater situational awareness than the numerical AGD. Additionally, the graphical AGD contained useful text information, such as the target aircraft and IM mode that were not able to be shown on the numerical AGD. Nevertheless, in the post-experiment

debrief pilots indicated that the numerical AGD would be sufficient, but not ideal, if the saliency of IM speed change alerting was improved.

## 5.2 Pilot Performance

In addition to the survey ratings provided by pilots, two pilot performance metrics were examined: the pilots' reaction time to new commanded speeds and how well pilots followed the IM commanded speeds. These metrics add supporting data to the workload and acceptability ratings provided by the pilots.

The first metric that was examined was the time it took pilots to recognize a new IM speed and begin dialing the speed into the MCP speed window (figure 17). The reaction time is, in essence, a time delay in the control loop. An Analysis of Variance (ANOVA) was used to examine the pilots' reaction time to IM speed changes. Since an ANOVA assumes that the data is normally distributed, a logarithm transformation was used to transform the reaction time distributions into normal distributions prior to conducting the ANOVA. The results indicate that pilots had significantly faster reaction times when using the graphical AGD ( $M=11.6$ ,  $SD=9.3$ ,  $N=263$ ), than when using the numerical AGD ( $M=18.6$ ,  $SD=16.1$ ,  $N=270$ ) ( $p<0.0001$ ). This is likely due to the additional saliency of the speed change alert on the graphical AGD. The graphical AGD used reverse video to alert pilots of IM speed changes, whereas the numerical AGD used an LED indicator that was significantly less noticeable. Pilot comments confirmed that they had difficulty noticing new IM speed commands when using the numerical AGD; however, pilot comments also suggested that the saliency of speed change alerting on the graphical AGD should be improved.

The second pilot performance metric that was examined was the aircraft's speed deviation from the IM speed. In this study, pilots were asked to use the fast/slow indicator on the AGD to remain within ten knots of their commanded speed. The root-mean-square of the aircraft's speed deviation from the commanded speed was examined to determine if the fast/slow indicator on the graphical AGD helped pilots follow the commanded speed. The IM aircraft did have a higher speed deviation when

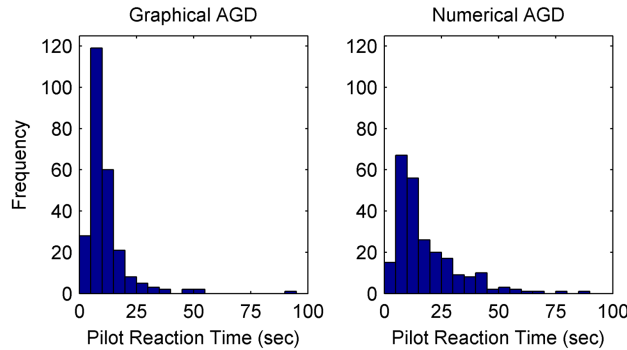


Figure 17: Pilot reaction time to new IM commanded speeds

using the numerical AGD ( $M=6.9$ ,  $SD=3.2$ ,  $N=32$ ) than when using the graphical AGD ( $M=5.6$ ,  $SD=3.0$ ,  $N=32$ ); however, the difference was not statistically significant ( $p=0.08$ ). Furthermore, the difference in the IM aircraft’s speed deviation between the graphical AGD and numerical AGD could have been caused by the differences in pilot reaction time, in which case the difference may disappear if the numerical AGD uses more salient speed change alerting in the future.

### 5.3 Spacing Algorithm Performance

Two measures of spacing algorithm performance were examined in this study: the spacing accuracy to the achieve-by point, and the rate at which IM speed changes were provided to pilots. The spacing accuracy at the achieve-by point describes how accurately and precisely the IM algorithm achieved the assigned spacing goal at the achieve-by point (table 5). The spacing accuracy was computed as the difference in time between when the target aircraft and IM aircraft crossed the final approach fix, subtracted from the assigned spacing interval. Within this experiment, the scenarios were scripted so that the assigned spacing goal was always reachable. As such, the spacing algorithm was expected to be capable of accurately and precisely achieving the spacing goal at the achieve-by point, and the data confirmed these expectations. The mean delivery accuracy was within five seconds ( $p<0.0001$ ), and the standard deviation of the delivery accuracy was less than five seconds ( $p=0.001$ ). Furthermore, all of the IM aircraft arrived within ten seconds of their spacing goal. These results are comparable to results from previous research [10, 14, 15, 17, 20]. An ANOVA revealed a statistically significant difference between the nominal and perturbation cases ( $p=0.001$ ); however, the difference is small and is not likely to have a large operational impact.

The rate at which speed changes were provided was an indication of pilot task load in this experiment, since the pilots were required to close the control loop by entering the commanded speeds into the MCP speed window. The speed change rate was computed for three different flight segments: the Center airspace, within the TRACON (not including final approach), and on final approach (figure 18). The speed change rates observed during this experiment increased as the aircraft approached the runway; however, they were always less than two speed changes per minute, which has been found to be acceptable in previous studies [5,6]. The pilots were also asked to rate the acceptability of the frequency of speed changes using a seven point scale ranging from one (completely disagree) to seven (completely agree). On average, the pilots moderately agreed that the speed change rate was acceptable ( $M=6.2$ ,  $SD=1.2$ ,  $N=128$ ), and moderately agreed that the IM commanded speeds were op-

Table 5: Delivery accuracy and precision at the final approach fix

	Numerical AGD		Graphical AGD	
	Mean (sec)	SD (sec)	Mean (sec)	SD (sec)
Nominal	-2.1	1.8	-2.0	1.6
Perturbation	0.1	2.1	0.2	4.1

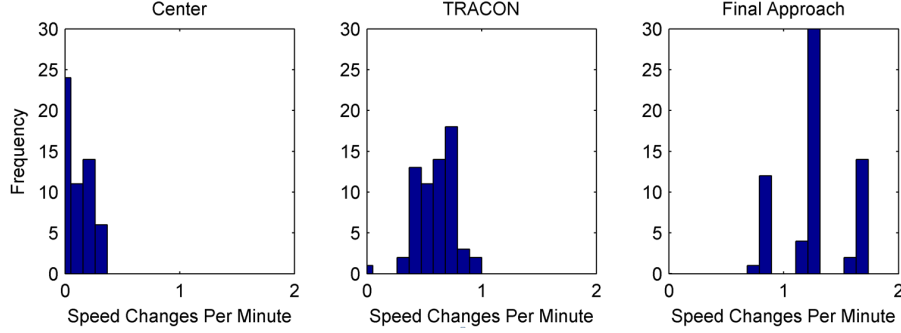


Figure 18: Histograms of IM speed change rate

rationally acceptable and appropriate ( $M=6.1$ ,  $SD=1.3$ ,  $N=128$ ). Pilot comments associated with the individual low ratings indicated speed command frequency, speed commands requiring configuration changes, and difficulty noticing speed commands as contributing factors.

## 6 Conclusions

This experiment investigated the acceptability and usability of retrofit IM displays while conducting nominal IM operations. Two different EFB interfaces and two different primary field-of-view AGDs were investigated. Overall, pilot ratings indicated that the pilot workload and time it took to enter information into both EFB interfaces was acceptable. However, pilot comments indicated that the amount of data entry required was high and that the operation would be more acceptable if the amount of data entry was reduced. A majority of pilots rated both the menu-entry and multi-entry EFB interfaces as acceptable; however, pilot comments during the post-experiment debrief indicated that pilots had a strong preference for the menu-entry EFB interface.

The graphical AGD was found to be more acceptable and intuitive than the numerical AGD, with pilot comments indicating that the main reason for the difference in acceptability was the alerting saliency of newly generated IM commanded speeds. Additional pilot comments indicated that they found the graphical trend indicators displayed on the graphical AGD more intuitive than the information displayed on the numerical AGD, but pilots only rated the information conveyed by the graphical indicators as moderately useful. Additionally, pilots ratings indicated that the additional text information shown on the graphical AGD was very useful. Based on the results from this study, future auxiliary IM displays should have the capability of displaying text information such as the target aircraft's ID and the operational state of the IM equipment in the forward field-of-view.



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# Appendix A: Post-Scenario Survey

## **I-SIM Human-in-the-Loop (HITL) Simulation Study**

### **POST-RUN QUESTIONNAIRE**

This questionnaire is intended to capture measures of workload and ratings for the events that occurred in the scenario that was just completed. You will be asked to complete a more extensive questionnaire at the end of the experiment, so please try and keep written comments as concise as possible.

#### **Administrative Questions**

**1. Please circle the scenario you just completed from the list below:**

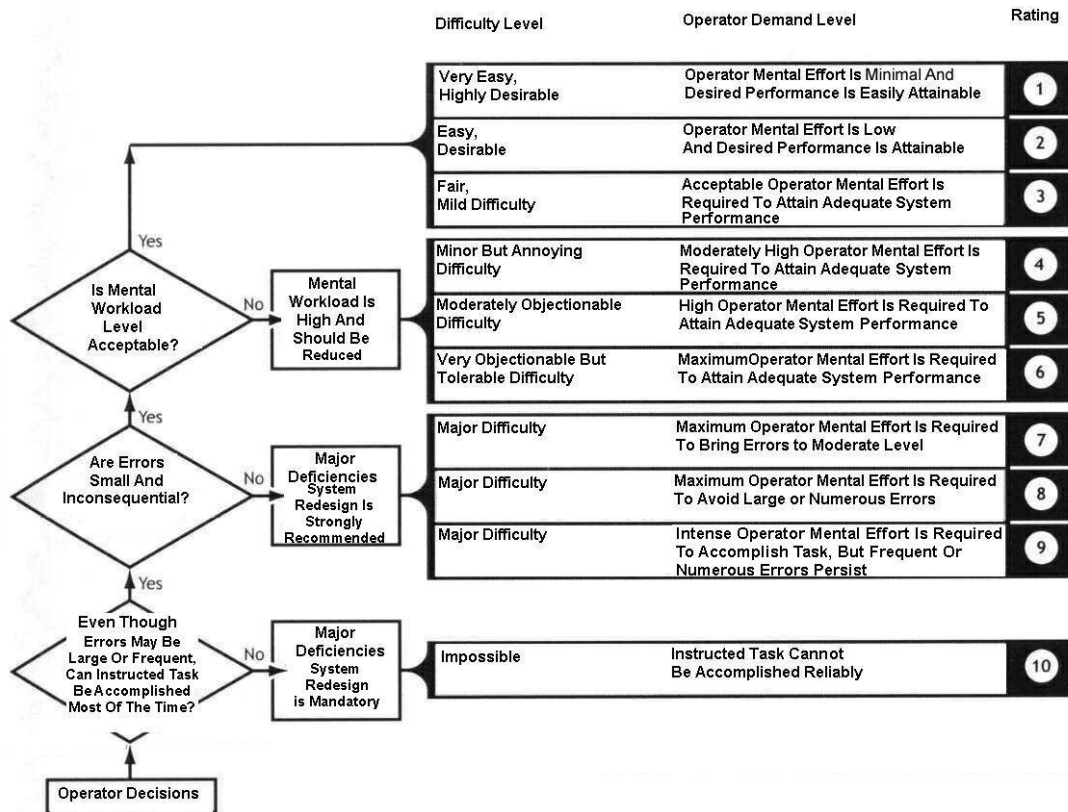
- Scenario 1
- Scenario 2
- Scenario 3
- Scenario 4
- Scenario 5
- Scenario 6
- Scenario 7
- Scenario 8

**2. Please circle your role during the scenario you just completed from the list below:**

- Pilot Flying
- Pilot Not Flying / Pilot Monitoring

## Data Entry Phase of Flight

### Average Workload Ratings (Modified Cooper-Harper)



3. Follow the flow chart above to select the average workload you experienced during the scenario you just completed.

➤ Rating of your average workload level while entering information into the EFB:

\_\_\_\_\_

4. Respond to each of the statements shown below using a scale ranging from “1” (Completely Disagree) to “7” (Completely Agree). Circle one number in conjunction with each statement.

	<u>Rating Scale</u>						
	1	2	3	4	5	6	7
	Completely Disagree					Completely Agree	
Relevant information, including operational plans, decisions, and changes in aircraft state were effectively communicated between yourself and your crewmember during the data entry phase of flight.	1	2	3	4	5	6	7
The time available for tasks during the data entry phase of flight was well managed.	1	2	3	4	5	6	7
The use of voice communications to provide the IM clearance was acceptable in this scenario.	1	2	3	4	5	6	7
The amount of head down time required to input information from the IM clearance into the EFB was acceptable.	1	2	3	4	5	6	7
During this scenario, entering IM clearance information into the EFB was easy and intuitive.	1	2	3	4	5	6	7
The flight crew procedures for receiving and entering an IM clearance were complete and acceptable.	1	2	3	4	5	6	7
Entering information into the EFB resulted in a minimal amount of frustration.	1	2	3	4	5	6	7

5. Please briefly explain any undesirable ratings from the statements above:

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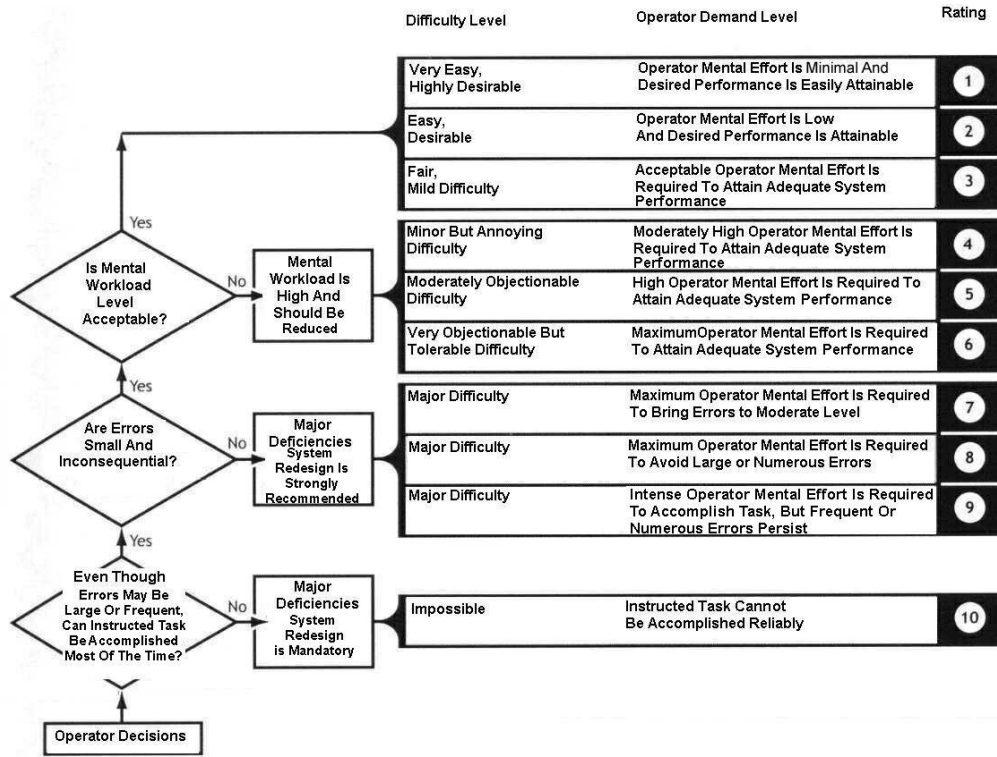
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## Monitoring IM Phase of Flight

### Average Workload Ratings (Modified Cooper-Harper)



6. Follow the flow chart above to select the average workload you experienced during the scenario you just completed.
- Rating of your average workload level while monitoring the FIM operation (when speed guidance was being provided) \_\_\_\_\_

7. Respond to each of the statements shown below using a scale ranging from “1” (Completely Disagree) to “7” (Completely Agree). Circle one number in conjunction with each statement.

	<u>Rating Scale</u>						
	1	2	3	4	5	6	7
	Completely Disagree					Completely Agree	
Relevant information, including operational plans, decisions, and changes in aircraft state were effectively communicated between yourself and your crewmember while monitoring the IM operation.	1	2	3	4	5	6	7
The time available for tasks was well managed while monitoring the IM operation.	1	2	3	4	5	6	7
The IM commanded speeds were operationally acceptable and appropriate.	1	2	3	4	5	6	7
The frequency of the IM speed commands was acceptable at all times throughout the scenario.	1	2	3	4	5	6	7
I understood why the IM commanded speeds were provided (i.e. the IM commanded speeds made sense).	1	2	3	4	5	6	7
The use of voice communications to provide the IM clearance(s) was acceptable in this scenario.	1	2	3	4	5	6	7
The flight crew procedures for the events in this scenario were complete and acceptable.	1	2	3	4	5	6	7
During this scenario, it was easy to obtain needed information from the primary field of view IM displays (i.e. the primary field of view displays were intuitive).	1	2	3	4	5	6	7
The primary field of view displays provided me with adequate situational awareness.	1	2	3	4	5	6	7

8. Please briefly explain any undesirable ratings from the statements above:

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## **All Phases of Flight**

**9. Describe any unusual or unexpected event(s) and your reaction(s), if applicable:**

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**10. (Optional) This space is reserved for any additional comments related to awareness and acceptability issues. If you have any clarifying comments or interesting observations related to awareness and acceptability issues, please provide them below.**

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## Appendix B: Post-Experiment Survey

### I-SIM Human-in-the-Loop (HITL) Simulation Study

#### POST-EXPERIMENT QUESTIONNAIRE

#### Post Experiment Questionnaire

This questionnaire is intended to gather your comments and suggestions regarding the experiment itself as well as Interval Management concept

This questionnaire contains items associated with each of the following categories:

- Simulator and Flight Scenarios
- Training
- Interval Management Procedures
- Interval Management Displays
- Spacing Tool
- Additional Comments

#### Simulator and Flight Scenarios

1. Was the workload required to operate the simulator much less than, the same as, or greater than the workload required to fly an actual aircraft?

	Moderately	Slightly		Slightly	Moderately	
Much More	More	More	The Same	Less	Less	Much Less
1	2	3	4	5	6	7

Please provide any additional comments regarding the simulator:

2. Please share your impressions of the flight scenarios (e.g., comment on their level of realism, appropriateness, and/or diversity) and comment on how the design of the scenarios impacted your ability to perform the spacing task:

## **Training**

- 3. Did you receive adequate training with respect to flying the simulator?**

YES \_\_\_\_

NO \_\_\_\_

**If not, briefly describe how simulator training can be improved:**

- 4. Did you receive adequate training with respect to the IM spacing procedure and the spacing tool?**

YES \_\_\_\_

NO \_\_\_\_

**If not, briefly describe how IM procedure or spacing tool training can be improved:**

- 5. Did you receive adequate training with respect to the entry and interpretation of information presented on the EFB interfaces?**

YES \_\_\_\_

NO \_\_\_\_

**If not, briefly describe how EFB training can be improved:**

- 6. Did you receive adequate training with respect to the interpretation of information presented on the CGD and AGD?**

YES \_\_\_\_

NO \_\_\_\_

**If not, briefly describe how AGD training can be improved:**

## Interval Management Procedures

7. Were the IM procedures complete, accurate, and logical?

YES \_\_\_\_

NO \_\_\_\_

Please provide any suggestions regarding the way(s) in which the general IM procedures may be improved:

8. Was the IM phraseology used in this experiment correct and intuitive?

YES \_\_\_\_

NO \_\_\_\_

If “no,” why not, and what could be done to improve the phraseology?

9. How difficult do you think it would be for a typical flight crew to learn and integrate the IM spacing procedures into their current daily operational flight procedures?

Very Difficult	Moderately Difficult	Slightly Difficult	Neutral	Slightly Easy	Moderately Easy	Very Easy
1	2	3	4	5	6	7

Briefly describe any challenges involved with integrating the IM procedures with existing procedures:

10. Do you think the division of tasks between the Pilot Flying (PF) and Pilot Monitoring (PM) was both desirable and fit within the current distribution of tasks between PF and PM?

YES \_\_\_\_

NO \_\_\_\_

If “no,” what was wrong with the division, and how would you reallocate the tasks?

11. Given the experience with IM that you gained during this simulation, what is your overall assessment of the safety of the spacing procedure compared with current day operations? (“Safety” in this question refers to your holistic opinion to include workload, awareness, position relative to other aircraft, etc.)

Not Safe At All	Moderately Less Safe	Slightly Less Safe	As Safe	Slightly More Safe	Moderately More Safe	Much More Safe
1	2	3	4	5	6	7

Briefly describe any characteristic or event that determined your rating (if appropriate):

## Interval Management Displays

### EFB Displays

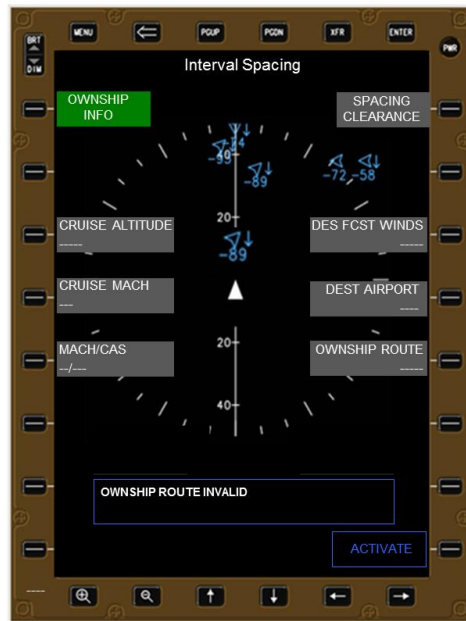


Figure 1: Menu-entry EFB interface



Figure 2: Multi-entry EFB interface

12. In general, did you find the process of entering IM clearance information into the menu-entry EFB interface easy and intuitive?

YES ☐

NO ☐

Please describe any improvements that could be made to the menu-entry EFB interface.

**13. Do you think the menu-entry EFB interface is a minimally acceptable interface for entering IM information (i.e. if the menu-entry EFB interface was placed on an aircraft, could you use it to enter IM information without compromising safety or experiencing too high of a workload).**

YES \_\_\_\_

NO \_\_\_\_

**If “no,” why isn’t the menu-entry EFB interface minimally acceptable?**

**14. In general, did you find the process of entering IM clearance information into the multi-entry EFB interface easy and intuitive?**

YES \_\_\_\_

NO \_\_\_\_

**Please describe any improvements that could be made to the multi-entry EFB interface**

**15. Do you think the multi-entry EFB interface is a minimally acceptable interface for entering IM information (i.e. if the multi-entry EFB interface was placed on an aircraft, could you use it to enter IM information without compromising safety or experiencing too high of a workload).**

YES \_\_\_\_

NO \_\_\_\_

**If “no,” why isn’t the multi-entry EFB interface minimally acceptable?**

**16. If you were conducting IM operations into a busy terminal area, would you prefer using the menu-entry or multi-entry EFB interface to enter IM information?**

Menu-entry \_\_\_\_

Multi-entry \_\_\_\_

**Please briefly explain your answer.**

*Primary Field of View Displays*

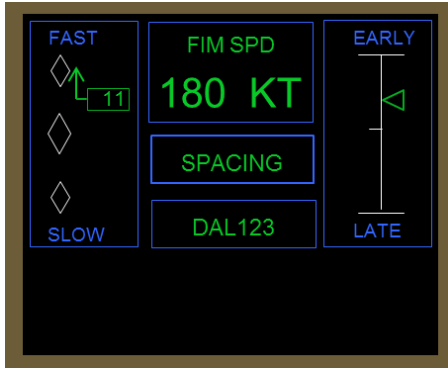


Figure 3: Configurable Glass Display (CGD)



Figure 4: ADS-B Guidance Display (AGD)

17. Using a scale ranging from “Detrimental (Hurts Performance)” to “Could Not Do IM Without”, rate the usefulness of the IM symbology on the Configurable Glass Display (CGD).

	Detrimental (Hurts Performance)	Not Useful At All	Slightly Useful	Moderately Useful	Very Useful	Required for IM
Fast/slow indicator	1	2	3	4	5	6
Fast/slow acceleration arrow	1	2	3	4	5	6
IM commanded speed	1	2	3	4	5	6
IM mode	1	2	3	4	5	6
Lead aircraft callsign	1	2	3	4	5	6
IM progress indicator	1	2	3	4	5	6
Drag required message	1	2	3	4	5	6

18. Please explain any undesirable ratings from the statements above.

19. Do you think the CGD is a minimally acceptable display for monitoring the IM operation (i.e. if the CGD was placed on an aircraft, could you use it to effectively monitor the IM operation without compromising safety or experiencing too high of a workload).

YES ☐

NO ☐

If “no,” why wouldn’t the CGD be minimally acceptable?

**20. Did the CGD provide you with the information you needed/desired to safely and correctly conduct IM, and was this information easy to obtain when needed?**

YES ☐

NO ☐

Please provide any changes you would make to the CGD to improve it?

**21. Using a scale ranging from “Detrimental (Hurts Performance)” to “Could Not Do IM Without”, rate the usefulness of the IM symbology on the ADS-B Guidance AGD.**

	Detrimental (Hurts Performance)	Not Useful At All	Slightly Useful	Moderately Useful	Very Useful	Required for IM
Commanded Speed	1	2	3	4	5	6
Fast/Slow Number	1	2	3	4	5	6
Spacing Error	1	2	3	4	5	6

**22. Please explain any undesirable ratings from the statements above.**

**23. Do you think the AGD is a minimally acceptable display for monitoring the IM operation (i.e. if the AGD was placed on an aircraft, could you use it to effectively monitor the IM operation without compromising safety or experiencing too high of a workload).**

YES ☐

NO ☐

If “no,” why wasn’t the AGD be minimally acceptable?

**24. Did the AGD provide you with the information you needed/desired to safely and correctly conduct IM, and was this information easy to obtain when needed?**

YES ☐

NO ☐

Please provide any changes you would make to the AGD to improve it?

**25. Would you prefer using the AGD or CGD to monitor the IM operation if you were conducting IM operations into a busy terminal area?**

AGD ☐

CGD ☐

**Please briefly explain your answer.**

## **Function Allocation and the Spacing Tool**

**26. Did following the IM commanded speed and procedure ever cause unexpected or undesirable behavior?**

YES ☐

NO ☐

**If “yes,” please explain what the unexpected or undesirable behavior was:**

**27. Did you find the responsibility of using onboard automation to achieve a spacing interval behind a lead aircraft acceptable (when ATC is responsible for separation)?**

YES ☐

NO ☐

**If “no,” why not, and what could be done to make the responsibility or workload acceptable?**

**28. Did you find your level of engagement with the IM automation acceptable (i.e. the level of decision making ability you had, and your understanding of the reasoning behind IM speeds that were commanded)?**

YES ☐

NO ☐

**Please explain your answer.**

## **Additional Comments**

**29. Do you have any additional comments about the experiment?**



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<p>NASA's first Air Traffic Management (ATM) Technology Demonstration(ATD-1) was created to transition the most mature ATM technologies from the laboratory to the National Airspace System. One selected technology is Interval Management (IM), which uses onboard aircraft automation to compute speeds that help the flight crew achieve and maintain precise spacing behind a preceding aircraft. Since ATD-1 focuses on a near-term environment, the ATD-1 flight demonstration prototype requires radio voice communication to issue an IM clearance. Retrofit IM displays will enable pilots to both enter information into the IM avionics and monitor IM operation. These displays could consist of an interface to enter data from an IM clearance and also an auxiliary display that presents critical information in the primary field-of-view. A human-in-the-loop experiment was conducted to examine usability and acceptability of retrofit IM displays, which flight crews found acceptable. Results also indicate the need for salient alerting when new speeds are generated and the desire to have a primary field of view display available that can display text and graphic trend indicators.</p>						
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